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Abstract

Calculations with SYNTRONVOID have been made to simulate the operation of a 600 MWe CANDU reactor in some 2½ years. The results look reasonable as regards obtainable burn up and reactivity changes, whereas the power distribution is badly represented due to 1) the quarter core symmetry used, 2) the lack of control system representation.

It is demonstrated that minor refuelling errors, i.e. untimely refuelling of a few scattered channels, do not lead to unacceptable power distributions. It is also demonstrated that care has to be taken in planning the refuelling strategy in order to avoid accumulation of fresh and almost fresh channels. An island of 10 fresh channels, as occurred in the calculations knocked down the power to about 2/3.

If it is felt that detailed 3D-calculations are desireable for guiding the operation it can be concluded that such calculations must be done on the full core.

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In a CANDU reactor the fuelling procedure is the very simple one of dayly opening one fuel channel to push 8 new bundles into it, collect the spent bundles and then close the channel again.

It is usually claimed, that these very frequent and small fuelling operations can be performed in such a way as to obtain a favourable power distribution. By making successive fuel additions from opposite ends of the reactor (bi-directional fuelling), the gross axial power distribution should be almost sinusoidal, and by taking the fuel in an inner (central) zone to a higher exposure than the rest in the outer (peripheral) zone, a radial flattening of the power should be obtained.

With the assumption that the continuous, bi-directional fuelling gives almost uniform nuclear properties all over the core (or uniform in each zone) the above statements are certainly true. But how uniform will the nuclear properties turn out to be in practice?

To get some bearing on the answer to this question a series of 3D-calculations were made, trying to simulate as closely as practical an actual fuelling scheme.

The Codes

Lattice calculations producing cell averaged two group cross sections as functions of burn up and power density were performed with the CCC program.

This programme performs a 76 groups, collision probability calculation (with UKNDL data) in an annular geometry, where the innermost zone contains all the UO_2 present in the cluster, the next zone contains all the cladding-, coolant-, pressure tube- and calandria tube material of the cluster, and the last zone is composed of the amount of moderator determined by the lattice pitch. The zones are subdivided to give 11 geometrical regions.

Resonance cross sections are obtained from the RESOREX routine, based on multi-multi-group slowing down calculations (1).

Thermal scattering cross sections for H and D are based on the NELKIN model, and for other nuclei on the free gas model.

The spectra obtained are used to give 10 groups condensed microscopic cross sections for all relevant nuclei.

Dancoff factors for the 3 fuel rings and the central rod in the 37 rod cluster are calculated with a collision probability method based on the MAMIC routine (2), (the MAMIC routine calculates collision probabilities for the true geometry, with the modification that all rods in a ring are equivalent).

The subsequent burn up calculations are made in 10 groups and collision probabilities for the true cluster geometry. A very detailed fission product calculation is done with the FIPO routine (3), treating 176 individual fission products. Two group diffusion parameters are delivered on punched cards as the ultimate result.

The over-all flux- and power distribution calculations were performed with a version of the SYNTRONVOID program (4), modified to facilitate the bi-directional fuelling scheme.

The SYNTRONVOID program consists of essentially four parts. A routine for calculating a three-dimensional flux distribution based on flux synthesis, a hydraulic routine which was not used in this case, a routine for calculating burn up and a routine for performing shuffling and refuelling operations.

In the original program only the last routine was changed in order to carry out the shuffling and refuelling scheme for the CANDU reactor.

In addition a minor change was made so that the program itself calculated the time step from one refuelling to the next. The condition applied was that the reactor should be just critical when refuelling took place.

In all calculations two trial functions were used. For the initial core, that is, before any shufflings took place, they were calculated as two-dimensional solutions to the diffusion equation for the axial midplane and for one of the end planes. For all the following calculations the trial functions were taken from the end planes. The trial functions were recalculated at each time step.

The calculations

Two group cross sections for SYNTRONVOID were produced by CCC for the following values of powerdensity (kW/cm) and burn up (MWd/kg U):

Power density (kW/cm): 2.405, 9.62, 19.24

Burn up (MWd/kg U): 0, 0.12, 0.36, 0.6, 1.08, 1.8, 3.0, 4.2, 5.4, 7.8, 10.2, 12.6, 15.0.

A cross section of the 600 MWe reactor core is shown in fig. 1. The refuelling strategy was chosen on the following criteria:

1) Quarter core symmetry was assumed
2) In one refuelling operation 4 channels in the quarter core were refuelled, 2 channels from the "inner" zone, 2 channels from the "outer" zone. If the two inner channels were refuelled from end A of the reactor, the two outer channels were refuelled from end B, and vice versa.
3) Two successive refuellings in the same zone were always from opposite ends.
4) The channels chosen for refuelling should be as remote as possible from other recently refuelled channels.

Refuelling of a channel means pushing the spent fuel forward such that 8 spent bundles come out, 4 spent bundles are moved from one end of the channel to the other, and 8 new bundles are introduced.

The reactor core was burned from fresh until zero reactivity and from then on refuelled according to table 1.

We later realized that we had started out very successfully with an erroneous refuelling operation, as a careful study of table 1 reveals. Channels (1,7) and (7,1) were refuelled by mistake in the very first operation and from the wrong end, too. This mistake did not have any strong effect. When the channels were visited again (operation 11), the only thing that happened was that the reactivity addition turned out to be extraordinarily small. The main results of the calculations are given in fig. 2 and table 1.

In fig. 2 the k_{eff}, the power form factor, the average in-core burn up, the exit burn up and the accumulated exit burn up are shown versus time. The most exciting feature of the figure is the rather high power peaks occurring at certain times. These peaks clearly demonstrate that one has to be rather careful when planning a refuelling strategy. It is possible, but has not been investigated, that

countermeasures by the distributed control system (adjuster rods and water compartments) can partly eliminate the peaks.

The power form factor, unspecified, as given by the Canadians, is 1.77. This low value is only obtained in our calculations during the first 10 refuellings, and never since. Again it should be stressed, that the control system may help considerably.

We suspect that the Canadian way of calculating the form factor is the following:

The two fuelling zones are homogenized and a 2- or 3-dimensional calculation is made. This approach clearly avoids all local peakings. To investigate this we calculated the average nuclear properties of the two zones from the detailed SYNTRONVOID output just after refuelling no. 26, which is the one with very high formfactor (2.67).

A DIFF2D rz-calculation was then made on the reactor geometry shown in fig. 3. The cross sections of the two zones (with the average burn ups of 5.528 MWd/kg U in the inner and 4.646 MWd/kg U in the outer zone) were obtained by interpolation in the SYNTRONVOID data for 9.62 kW/cm.

The power form factor obtained in this calculation was 2.23. The radial power distribution in the mid-plane is shown in fig. 4, with the corresponding results from SYNTRONVOID marked as x for points along x = 0 and as 0 for points along x = y.

It is seen from the figure, that the two power distributions (the "true" SYNTRONVOID distribution and the idealised DIFF2D distribution) do agree fairly well, except for the oscillations of the "true" distribution, due to different burn ups in the channels. In this case, an exceptional large overshoot happens to occur in the central channels, thus determining the formfactor. A number of conclusions can be drawn from this comparison.

1) The "homogeneous" form factor of 2.23 shows that a wrong refuelling rate ratio for the two zones has been chosen. The ratio of the burn up in the inner zone to the burnup in the outer zone should be higher, thus enforcing a more pronounced flux- and power flattering.

   As an illustration of this statement one more DIFF2D calculation was made, this time with cross sections corresponding to

6.0 MWd/ kg U in the inner zone and 4.2 MWd/kg U in the outer zone. The formfactor dropped to 1.86 and the new distribution is shown in fig. 4. It seems quite feasible to obtain a "homogeneous" formfactor of 1.77.

2) The demand of a very careful scattering of the refuelled channels is stressed. In our calculation the quarter core symmetry leads to an accumulation of fresh elements when a centrally placed channel is refuelled. Thus, refuelling operation no. 26 places 8 fresh channels in a ring around the four central channels, which, by the way, were refuelled in operation no. 23. Such accumulation can be avoided in practice and hence the results of the present exercise are rather uninteresting as regards the formfactor.

3) If reliable results are to be obtained, full core calculations must be performed with all their demands on computer time and storage capacity.

Summing up

Calculations with SYNTRONVOID have been made to simulate the operation of a 600 MWe CANDU reactor in some 2 1/2 years. The results look reasonable as regards obtainable burn up and reactivity changes, whereas the power distribution is badly represented due to [1] the quarter core symmetry used, [2] the lack of control system representation.

It is demonstrated that minor refuelling errors, i.e. untimely refuelling of a few scattered channels, do not lead to unacceptable power distributions. It is also demonstrated that care has to be taken in planning the refuelling strategy in order to avoid accumulation of fresh and almost fresh channels. An island of 10 fresh channels, as occurred in the calculations knocked down the power to about 2/3.

If it is felt that detailed 3D-calculations are desireable for guiding the operation it can be concluded that such calculations must be done on the full core.

Table 1

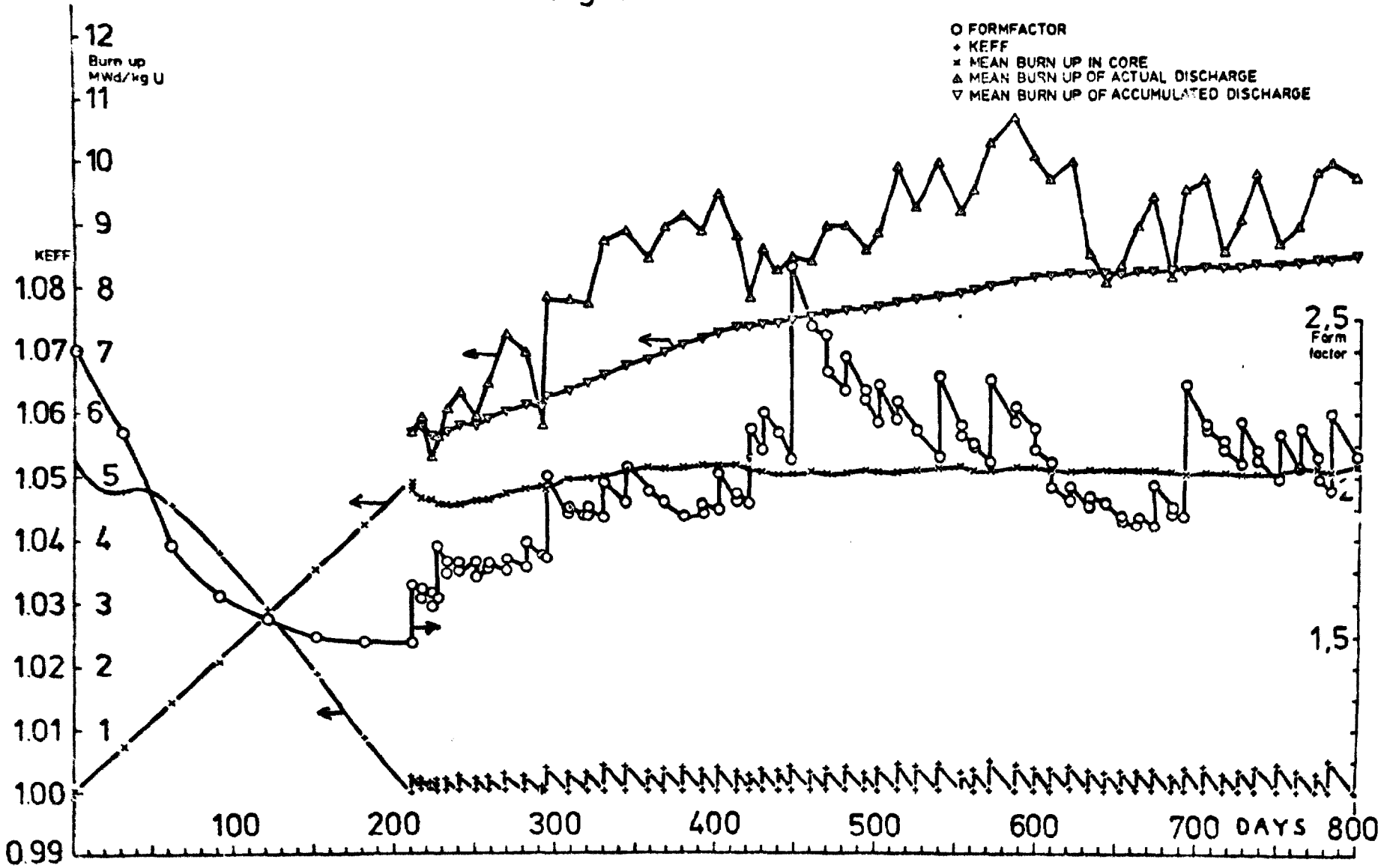
Fuelling scheme:

No.	Channels fuelled from end A of reactor (x,y)	Channels fuelled from end B of reactor (x,y)	Δk_{eff} (mk)	Power form factor and position PFF	(x,y,z)
1	(1,1)(5,5)	(7,1)(1,7),(8,1)(1,8)	2.33	1.65	(1,1,4)
2	(5,7)(7,5)	(1,4)(4,1)	1.72	1.61	(1,1,4)
3	(3,7)(7,3)	(4,9)(9,4)	1.21	1.59	(1,1,4)
4	(2,10)(10,2)	(1,2)(2,1)	1.65	1.78	(1,2,9)
5	(3,5)(5,3)	(6,7)(7,6)	1.81	1.69	(1,2,9)
6	(2,8)(8,2)	(3,6)(6,3)	2.20	1.70	(1,2,9)
7	(2,2)(6,6)	(1,10)(10,1)	1.75	1.68	(1,2,9)
8	(6,8)(8,6)	(1,6)(6,1)	2.16	1.72	(1,2,9)
9	(2,4)(4,2)	(3,8)(8,3)	2.78	1.74	(1,2,7)
10	(7,7)(8,8)	(3,4)(4,3)	2.44	1.79	(1,2,7)
11	(1,7)(7,1)	(6,9)(9,6)	0.56	1.75	(1,2,7)
12	(4,8)(8,4)	(2,3)(3,2)	3.55	2.00	(1,2,7)
13	(2,6)(6,2)	(2,9)(9,2)	3.04	1.90	(1,2,7)
14	(5,9)(9,5)	(4,5)(5,4)	2.81	1.90	(2,3,7)
15	(1,3)(3,1)	(5,8)(8,5)	4.14	1.98	(1,3,7)
16	(1,9)(9,1)	(2,5)(5,2)	4.03	2.03	(2,3,7)
17	(4,6)(6,4)	(7,8)(8,7)	3.07	1.95	(1,3,7)
18	(3,9)(9,3)	(5,6)(6,5)	3.48	1.92	(1,3,7)
19	(1,5)(5,1)	(3,10)(10,3)	3.73	1.97	(1,3,7)
20	(7,9)(9,7)	(2,7)(7,2)	3.29	1.91	(2,5,7)
21	(3,3)(4,4)	(5,10)(10,5)	3.89	2.01	(3,3,6)
22	(1,11)(11,1)	(4,7)(7,4)	2.98	1.94	(3,3,7)
23	(1,1)(5,5)	(2,11)(11,2)	2.49	2.15	(1,1,7)
24	(4,10)(10,4)	(1,4)(4,1)	3.16	2.20	(1,1,6)
25	(3,7)(7,3)	(1,8)(8,1)	3.00	2.06	(1,1,7)
26	(3,11)(11,3)	(1,2)(2,1)	3.46	2.67	(1,1,6)
27	(3,5)(5,3)	(4,9)(9,4)	3.05	2.47	(1,1,6)
28	(5,7)(7,5)	(3,6)(6,3)	3.45	2.33	(1,1,6)
29	(2,2)(6,6)	(6,7)(7,6)	3.69	2.38	(1,1,7)
30	(2,10)(10,2)	(1,6)(6,1)	2.72	2.24	(1,1,7)
31	(2,4)(4,2)	(1,10)(10,1)	3.32	2.29	(1,1,7)
32	(2,8)(8,2)	(3,4)(4,3)	4.29	2.24	(2,2,7)
33	(1,7)(7,1)	(3,8)(8,3)	3.85	2.14	(2,2,6)

Fuelling scheme (cont.'d):

No.	A end (x,y)	B end (x,y)	Δk_{eff}	PFF	(x,y,z)
34	(6,8)(8,6)	(2,3)(3,2)	4.19	2.32	(2,2,6)
35	(2,6)(6,2)	(6,9)(9,6)	3.15	2.13	(2,3,6)
36	(7,7)(8,8)	(4,5)(5,4)	3.32	2.09	(2,3,6)
37	(1,3)(3,1)	(2,9)(9,2)	4.53	2.31	(1,3,6)
38	(4,8)(8,4)	(2,5)(5,2)	4.40	2.22	(1,3,6)
39	(4,6)(6,4)	(5,8)(8,5)	3.48	2.08	(1,3,6)
40	(5,9)(9,5)	(5,6)(6,5)	3.24	1.96	(1,3,6)
41	(1,5(5,1)	(7,8)(8,7)	3.66	1.96	(1,5,6)
42	(1,9)(9,1)	(2,7)(7,2)	3.11	1.93	(1,5,6)
43	(3,3)(4,4)	(3,10)(10,3)	2.87	1.91	(1,5,7)
44	(3,9)(9,3)	(4,7)(7,4)	3.07	1.87	(1,5,6)
45	(1,1)(5,5)	(5,10)(10,5)	2.94	1.87	(5,5,6)
46	(7,9)(9,7)	(1,4)(4,1)	3.28	1.97	(1,4,6)
47	(3,7)(7,3)	(2,11)(11,2)	2.29	1.88	(1,4,6)
48	(4,10)(10,4)	(1,2)(2,1)	3.66	2.29	(1,1,6)
49	(3,5)(5,3)	(1,8)(8,1)	3.96	2.16	(1,1,6)
50	(3,11)(11,3)	(3,6)(6,3)	2.65	2.08	(1,1,6)
51	(2,2)(6,6)	(4,9)(9,4)	3.45	2.17	(1,1,6)
52	(5,7)(7,5)	(1,6)(6,1)	3.91	2.05	(1,1,6)
53	(2.4)(4.2)	(6,7)(7,6)	4.02	2.13	(1,2,6)
54	(2,10)(10,2)	(3,4)(4,3)	3.40	2.15	(2,2,6)
55	(1,7)(7,1)	(1,10)(10,1)	2.92	1.99	(2,2,6)
56	(2,8)(8,2)	(2,3)(3,2)	4.68	2.20	(2,2,6)
57	(2,6)(6,2)	(3,8)(8,3)	4.07	2.04	(2,3,6)

Fig. 2


O FORMFACTOR
+ KEFF
× MEAN BURN UP IN CORE
△ MEAN BURN UP OF ACTUAL DISCHARGE
▽ MEAN BURN UP OF ACCUMULATED DISCHARGE
Burn up
MWd/kg U
KEFF
Form factor
DAYS
12
11
10
9
8
7
6
5
4
3
2
1
1.08
1.07
1.06
1.05
1.04
1.03
1.02
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1.00
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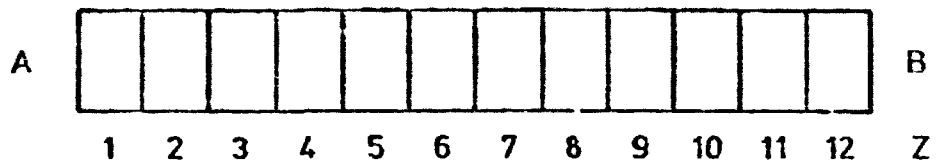
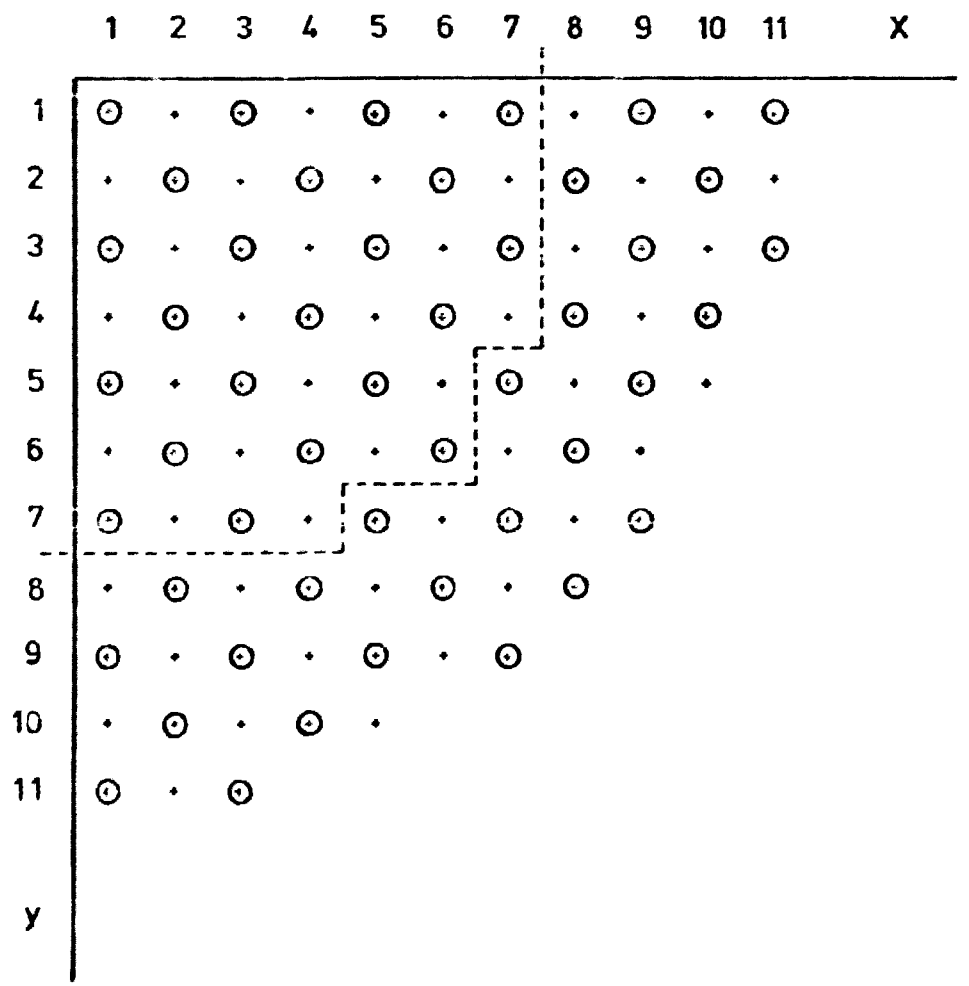
2,5
1,5
100
200
300
400
500
600
700
800

Fig. 1



Fuel channel with ends A and B

The z coordinate is the number of bundles from A

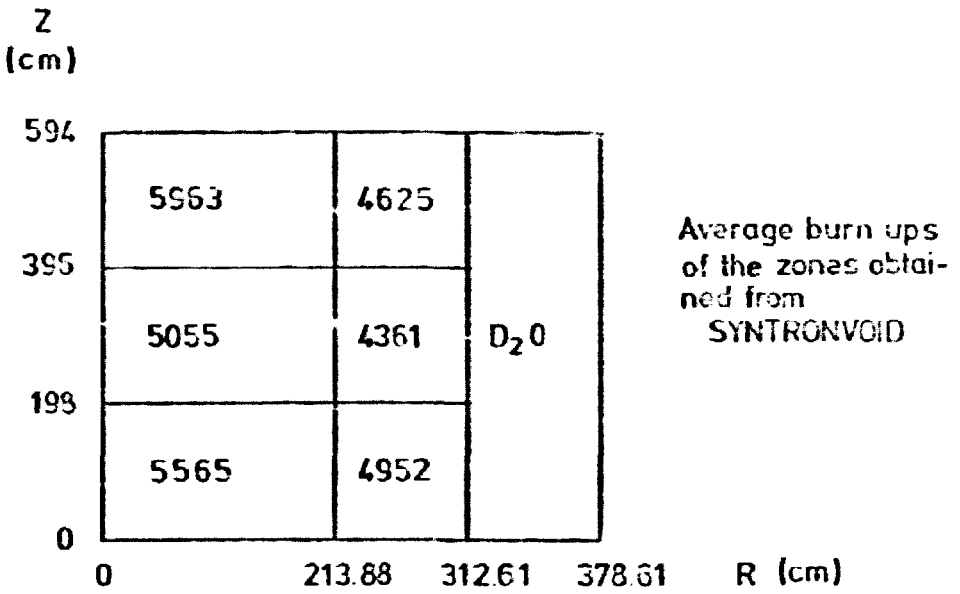


Quarter core cross section.

⊙ Fuel channels which are refulled from end A.

• ——————— // ——————— B.

Dotted line indicates boundary between inner and outer refuelling zone



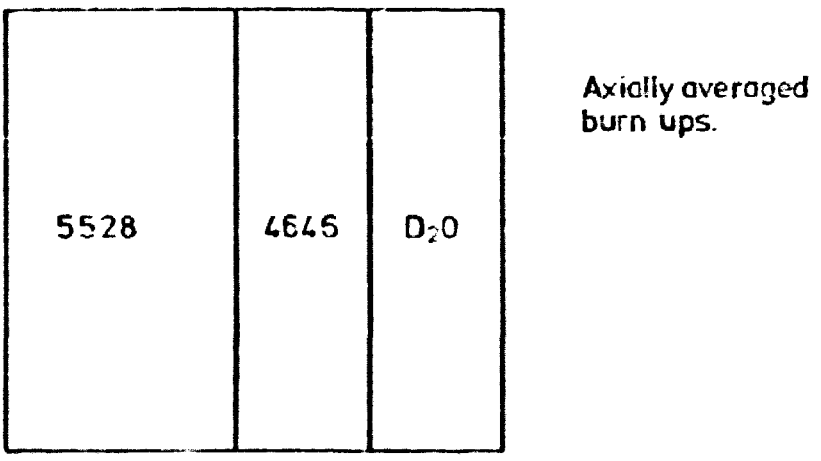


Fig 3

Geometry for DIFF2D calculations

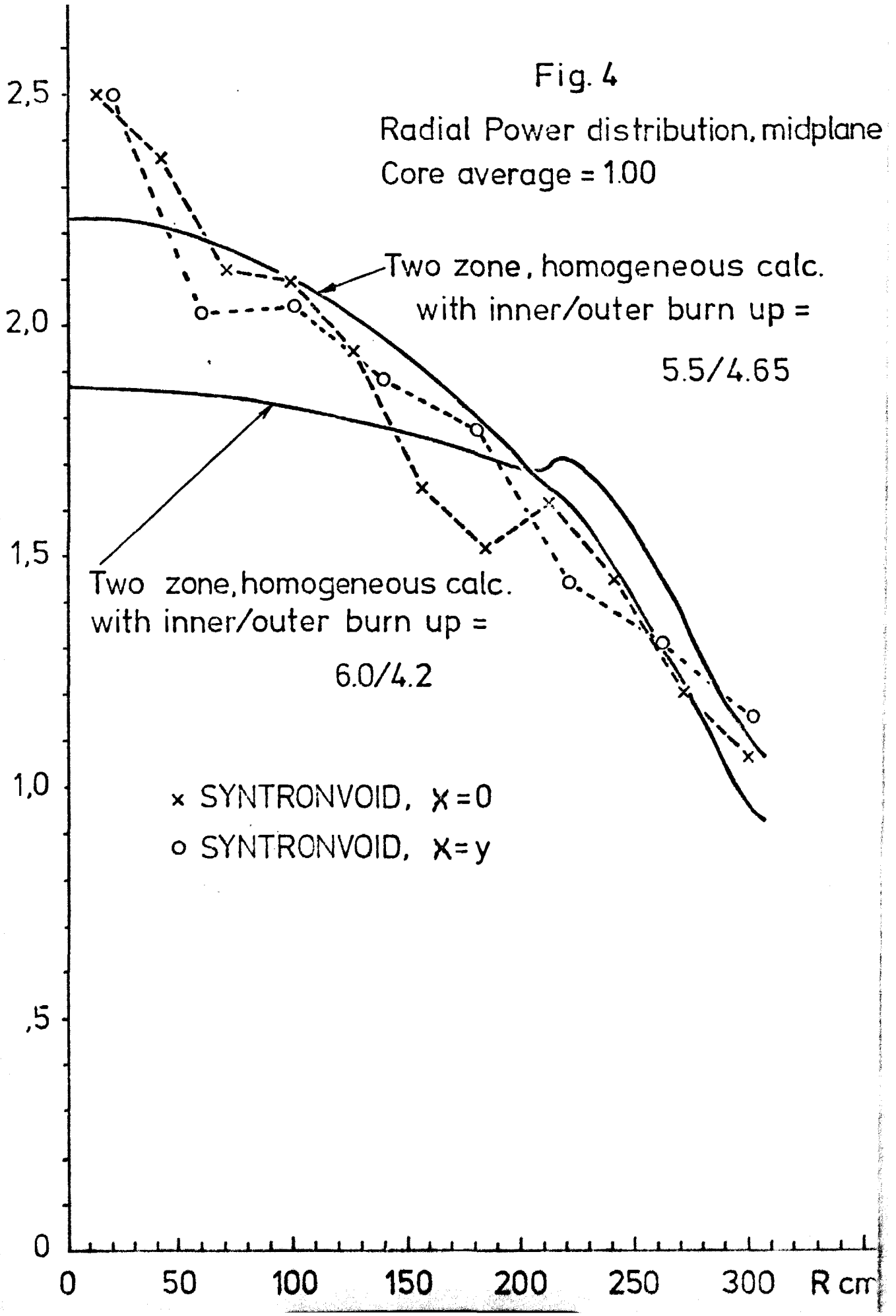


Fig. 4
Radial Power distribution, midplane
Core average = 1.00
Two zone, homogeneous calc.
with inner/outer burn up =
5.5/4.65
Two zone, homogeneous calc.
with inner/outer burn up =
6.0/4.2
× SYNTRONVOID, X = 0
o SYNTRONVOID, X = y
2,5
2,0
1,5
1,0
,5
0
0
50
100
150
200
250
300
R cm